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Determination of Appropriate Type of Ground Model for Studying Seismic Waves Propagating in Ground

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Abstract: Seismic wave is transmitted to buildings and structures through the soil, so choosing an appropriate soil model to represent the seismic waves propagating in the soil ensures that the problem is accurate and reliable. In this article, several ground models representing seismic waves propagating in the ground using the Plaxis 3D program are highlighted and conclusions are given.

Keywords: seismic wave, soil models, finite element method (FEM), modulus of elasticity, Poisson's coefficient, theory of elasticity.

INTRODUCTION. When solving the problem of wave propagation in the ground using the finite element method, the choice of the ground model is of great importance [1,2,3]. The world's leading experts in the field say that the model used to solve static problems related to soil is unsuitable for dynamic problems. In dynamic processes, its parameters change over time due to the decrease in soil hardness and the change of molecular networks [4,5]. Ignoring this confirmation calls into question the validity of the numerical results obtained.

The mechanical behavior of soils and rocks can be modeled with varying degrees of accuracy. For example, Hooke's law of linear, isotropic elasticity can be considered the simplest existing stress-strain relationship. Since it includes only two key parameters, Young's modulus E and Poisson's ratio n, it lacks precision to account for important properties of soil and rock. A linear elastic plastic model (Mor-Coulomb) can be considered as a first-order approximation of the state of the soil or rock. However, Plaxis software includes more advanced material models with unique properties such as pressure dependence of stiffness, critical state, anisotropy, swelling and shrinkage. Users are advised to use advanced models to more realistically reflect soil and rock movements, and as a result, more accurate results are obtained from the calculations performed using Plaxis 3D software.

Let's take a look at the types of models used to represent soil and rock behavior.

1. **The linear elastic model** is based on Hooke's law of isotropic elasticity. It includes two main elastic parameters, namely Young's modulus E and Poisson's ratio ν. Although the linear elastic model is not suitable for modeling soil, it can be used to model solid volumes in soil such as concrete walls or undisturbed rock formations.
2. **Mohr-Coulomb model.** The linear elastic perfectly plastic Mohr-Coulomb model includes five input parameters, namely E-modulus of elasticity and n-Poisson's ratio for soil elasticity; for soil plasticity, φ-angle of internal friction and c-relative adhesion and πs-expansion angle. The Mohr-Coulomb model represents a "first-order" approximation of the motion of a point in a soil or rock mass. It is recommended to use this model to analyze the considered problem. For each layer, a constant average stiffness or an increasing stiffness with increasing linear bond shear is evaluated. Due to the constant stiffness, the calculations are performed relatively quickly and the initial calculation of the deformations is obtained.

In the case of dynamic applications, alternative or additional parameters can be used to determine the stiffness based on wave velocity. These parameters are Vp and Vs.

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3. Hardening soil model. The Hardening Soil (HS) model is an advanced model for representing soil behavior. Unlike the Mohr-Coulomb model, the hardening soil HS model also takes into account the pressure dependence of the stiffness modulus. This means that all stiffnesses increase with pressure. Thus, all three input stiffnesses relate to a reference stress that is generally taken as 100 kPa (1 bar).

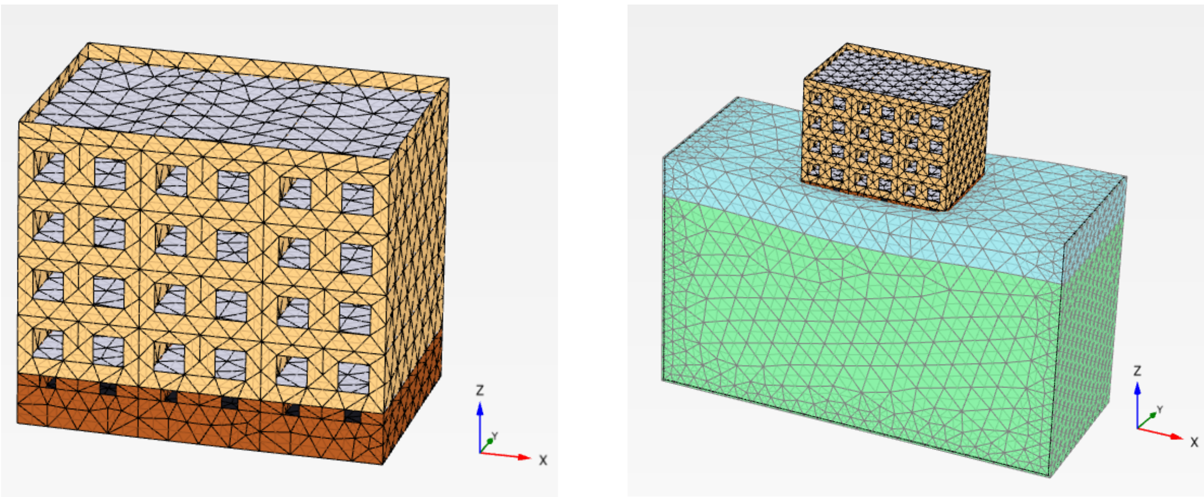
When the HS model is used in dynamic calculations, the elastic stiffness parameter E_{ref} should be chosen so that the model correctly predicts the ground wave velocity. This typically requires a small deformation stiffness for E_{ref} rather than just the unloading-reload stiffness. Rayleigh damping can be defined to represent the damping characteristics of soil under cyclic loading. Some of the limitations of the HS model in dynamic applications can be overcome using the HS small model.

4. Hardening soil model at small deformations (HS small). The HS small model is a modification of the above HS model, which increases the stiffness of the grunts at small deformations. The advanced features of the HS small model are clearly visible under heavy workloads. In this case, the HS small model provides more reliable displacement values than the HS model.

Since HS small model includes soil loading history and strain-dependent stiffness, it can be used to model cyclic loading to some extent. Using the HS small model usually takes longer.

Based on the information presented above, when solving dynamic problems such as wave propagation in the ground, it is possible to obtain more accurate results by using variable parameters depending on the deformation of the HS small model, rather than the constant values of the ground parameters in statics. In order to choose a model that more accurately illuminates the seismic waves propagating in the ground using Plaxis 3D software, it was clarified by solving the problem as follows. Using the Mor-Coulomb and HS Small models to represent seismic waves in the ground with the help of the program, two problems with the same geometric dimensions were solved and their results were compared.

MATERIALS AND METHODS. In order to solve the problem, a model with a ground massif 20 m wide and 50 m long and a building placed on it was selected. The issue does not take into account the influence of underground water. As an example, a 4-story brick building with a ground floor was selected (Fig. 1a).



a *b*

Fig. 1. a) general view of the building, b) a model of the problem divided into finite elements

Strength and mechanical indicators of building construction materials are presented in the following table:Table 1

№	Modulus of elasticity	Poisson's ratio	Comparative weight	Brand
Unit of measure	*kg/sm²*	-	*kg/m³*	-
overlaps and coatings	*E=3060000*	*ν=0,2*	*γ=2500*	300M
Foundation	*E=2700000*	*ν=0,2*	*γ=2500*	200M
Outer wall	*E=500000*	*ν=0,25*	*γ=1800*	75M

We use the finite element method to solve the problem.

The shapes of the finite elements were chosen as irregular tetrahedrons. When we divided the model into finite elements, a mechanical system consisting of 10119 elements and 26284 nodes was formed.

The problem is solved by referring to the problem of the theory of elasticity.

In this problem, the infinite plane is replaced by a finite sphere. In this case, the following conditions are set, which ensure that the waves tend to infinity at the boundaries.

$$\left.\begin{matrix}\boldsymbol{\sigma_x = a\rho V_p \dot{u}}\\ \boldsymbol{\tau_{yz} = b\rho V_s \dot{u}}\\ \boldsymbol{\tau_{zy} = b\rho V_s \dot{w}}\end{matrix}\right\} \left.\begin{matrix}\boldsymbol{\sigma_y = a\rho V_p \dot{v}}\\ \boldsymbol{\tau_{xz} = b\rho V_s \dot{w}}\\ \boldsymbol{\tau_{zx} = b\rho V_s \dot{u}}\end{matrix}\right\} \left.\begin{matrix}\boldsymbol{\sigma_z = a\rho V_p \dot{w}}\\ \boldsymbol{\tau_{xy} = b\rho V_s \dot{u}}\\ \boldsymbol{\tau_{yx} = b\rho V_s \dot{v}}\end{matrix}\right\} \quad (1)$$

Here $\boldsymbol{\sigma}$ and $\boldsymbol{\tau}$ stresses; $\dot{\mathbf{u}}, \dot{\mathbf{v}}$ and $\dot{\mathbf{w}}$ are the projections of the speeds of the limit points on axes; $\mathbf{V_p}$ and $\mathbf{V_s}$ are the speeds of P and S waves; **a** and **b** are dimensionless parameters; $\boldsymbol{\rho}$ is the density of the material.

The kinematic relationship can be formulated as follows:

$$\boldsymbol{\varepsilon = Lu} \quad (2)$$

L^T - differential operator transponir

$$\mathbf{L^T} = \begin{bmatrix} \frac{\partial}{\partial x} & 0 & 0 & \frac{\partial}{\partial y} & 0 & \frac{\partial}{\partial z} \\ 0 & \frac{\partial}{\partial y} & 0 & \frac{\partial}{\partial x} & \frac{\partial}{\partial z} & 0 \\ 0 & 0 & \frac{\partial}{\partial z} & 0 & \frac{\partial}{\partial y} & \frac{\partial}{\partial x} \end{bmatrix} \quad (3)$$

In general, each element material can have an initial deformation due to temperature changes, precipitation or crystallization. If we denote this strain by $\{\varepsilon_0\}$, the stress is determined by the difference between the existing strain and the initial strain. It is also convenient to assume that there is some measurable residual stress at the time being considered. This voltage is added to the total voltage expression. When considering the material of the object as elastic, the relationship between stress and deformation is linear:

$$\{\boldsymbol{\sigma}\} = [\mathbf{D}](\{\boldsymbol{\varepsilon}\} - \{\boldsymbol{\varepsilon_0}\}) + \{\boldsymbol{\sigma_0}\} \quad (4)$$

Here [D] is the elasticity matrix representing material properties.

In particular, in the case of plane stress, the three components of stress corresponding to deformation are written as follows:

$$\{\boldsymbol{\sigma}\} = \begin{Bmatrix} \boldsymbol{\sigma_x} \\ \boldsymbol{\sigma_y} \\ \boldsymbol{\tau_{xy}} \end{Bmatrix}$$

The matrix [D] is determined from the following relationship between stress and strain:

$$\boldsymbol{\varepsilon_x - (\varepsilon_x)_0 = \frac{1}{E}\sigma_x - \frac{v}{E}\sigma_y;\ \varepsilon_y - (\varepsilon_y)_0 = -\frac{v}{E}\sigma_x + \frac{1}{E}\sigma_y;}$$

$$\boldsymbol{\gamma_{xy} - (\gamma_{xy})_0 = \frac{2 + (1 + v)}{E}\tau_{xy};}$$

From this:

$$[\mathbf{D}] = \frac{\mathbf{E}}{\mathbf{1 - v^2}} \begin{bmatrix} \mathbf{1} & \mathbf{v} & \mathbf{0} \\ \mathbf{v} & \mathbf{1} & \mathbf{0} \\ \mathbf{0} & \mathbf{0} & \frac{\mathbf{1 - v}}{\mathbf{2}} \end{bmatrix} \quad (5)$$

The system of time-dependent motion differential equations of a discrete system created by applying the finite element method to the model under the influence of dynamic load is expressed as follows [6,7]:

$$[\mathbf{M}]\{\ddot{\mathbf{u}}(\mathbf{t})\} + [\mathbf{C}]\{\dot{\mathbf{u}}(\mathbf{t})\} + [\mathbf{K}]\{\mathbf{u}(\mathbf{t})\} = \{\mathbf{F}(\mathbf{t})\} \quad (6)$$

The order of this equation is 12718×3=38154.

Here $[\mathbf{M}]$ is the mass matrix, $[\mathbf{C}]$ is the damping matrix, $[\mathbf{K}]$ is t stiffness matrix, and $\{\mathbf{F}(\mathbf{t})\}$ is the dynamic load vector. $\{\mathbf{u}(\mathbf{t})\}$ - displacement, $\{\mathbf{u}(\mathbf{t})\}$ −velocity, and $\{\ddot{\mathbf{u}}(\mathbf{t})\}$ − acceleration are continuous functions of time. Here the theory is described on the basis of linear elasticity theory. The [M]-matrix takes into account the mass of materials (soil + water + any structure).

In the numerical representation of the dynamics issue, the formation of iteration over time is an important factor for the stability and accuracy of the calculation process.

We accept Newmark's time iteration coefficients as $\alpha = 0.25$ and $\beta = 0.5$.

In this case, comparisons were made by introducing the same accelerogram to Mor-Coulomb and HS Small models of buildings with the same structural dimensions. In solving this problem, the seismic wave accelerogram is considered to be influenced by the selected model (Fig. 2). The used accelerogram was recorded as a result of an earthquake that occurred in the Tashkent region of the Republic of Uzbekistan.

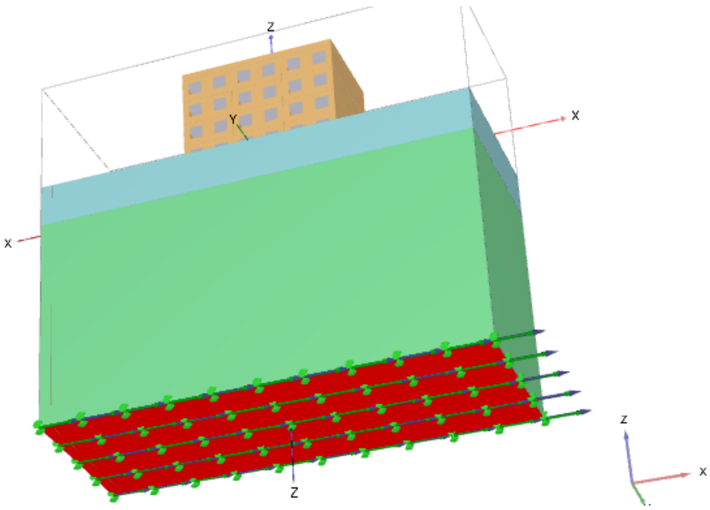


Fig. 2. Applying the accelerogram to the selected model

The soil used in the models consists of two layers, and the characteristics of the soil included in the Mohr-Coulomb model are listed in Table 2.Table 2

Soil characteristics \ Soil type	Layer 1. Sandy soil	Layer 2. Stones with up to 30% sand and clay filler
№	2	3
Type of model used	Mohr-Coulomb	Mohr-Coulomb
Density in the dry state - γ_{uns}[kN/m^3]	14,8	19,5
Density when saturated with water - γ_{sat} [kN/m^3]	16,9	20,5
Angle of internal friction - φ [º]	23	38
Expansion Angle - ψ [º]	1	2
Cohesion - c_{ref} [kN/m^2]	6	-
Velocity of longitudinal wave - Vp [m/s]	116	135
Velocity of eransverse wave - Vs [m/s]	225	253
Modulus of elasticity - E [kN/m^2]	$6{,}0\cdot10^4$	$8{,}0\cdot10^4$
Poisson's ratio - ν	0,32	0,3

The properties of soil included in the HS Small model are presented in Table 3.

Table 3

№	Parameters name	Belgilanishi	1-qatlam. Suglinka	2-qatlam. Galichnik	O'lchov birligi
1	Type of model used	Model	HS small	HS small	-
2	Density in the dry state	γ_{unsat}	14,8	19,5	kN/m^3
3	Density when saturated with water	γ_{sat}	16,9	20,5	kN/m^3
4	The modulus of elasticity of the soil	E_0^{ref}	$1{,}92\cdot10^4$	$2{,}13\cdot10^4$	kN/m^2
5	Tangential modulus of stiffness at initial loading	E_{oed}^{ref}	$2{,}4\cdot10^4$	$2.67\cdot10^4$	kN/m^2
6	Modulus of elasticity of soil under reloading	E_{ur}^{ref}	$7{,}2\cdot10^4$	$8{,}0\cdot10^4$	kN/m^2
7	Cohesion	c'_{ref}	6	-	kN/m^2
8	Angle of friction	φ'	23	38	°
9	Angle of expansion	ψ	1,0	2,0	°
10	Shear strain at Gs = 0.722G_0	$\gamma_{0.7}$	$1{,}2\cdot10^{-4}$	$1{,}2\cdot10^{-4}$	-
11	Shear modulus at very small deformations	G_0^{ref}	$3{,}0\cdot10^4$	$3{,}5\cdot10^4$	kN/m^2
12	Poisson's ratio	ν'_{ur}	0,32	0,3	-

RESULTS AND DISCUSSIN

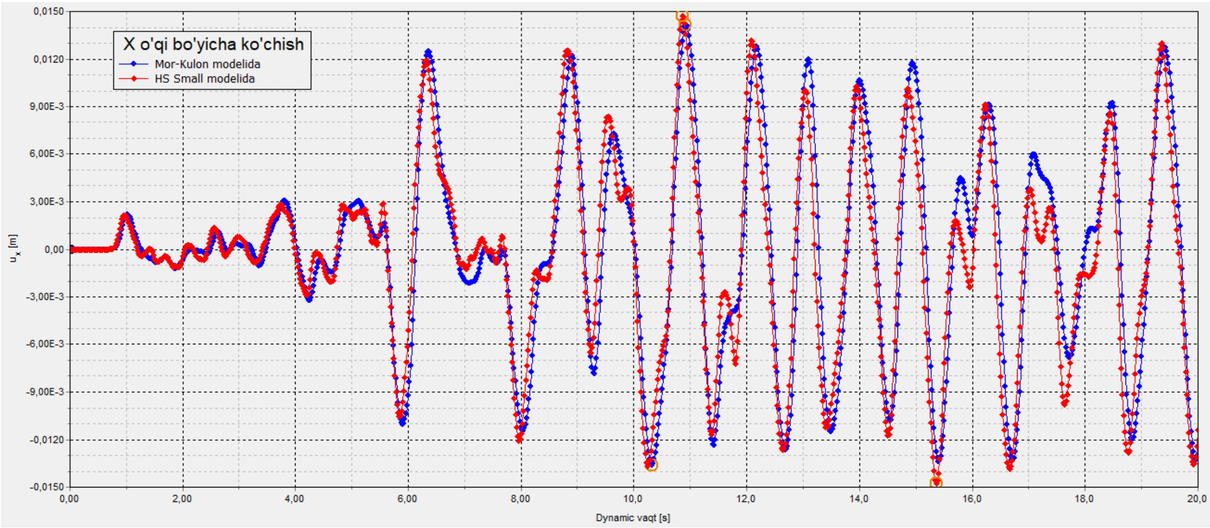


Fig. 3. A graph of the x-axis displacement of a seismic wave

Accelerogram results reflected in Mohr-Coulomb and HS Small models are obtained from a point on the floor of the building (in both models, the location of the coordinate axis is the same point). According to it, the maximum value of the displacement of the seismic wave along the x axis in the Mohr-Coulomb model is $u_{xmax}=1.39\ cm$, and in the building of the HS Small model it is $u_{xmax}=1.5\ cm$.

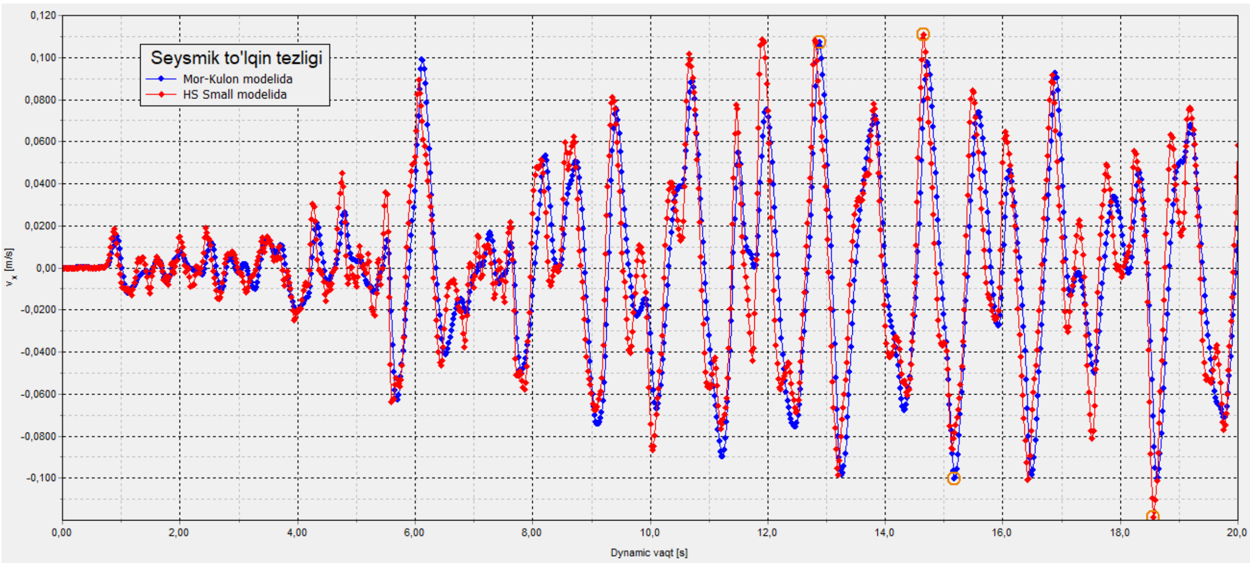


Fig. 4. A graph of the velocity of a seismic wave along the x-axis

As in the displacement graph, the maximum value of the x-axis velocity of the seismic wave in the Mohr-Coulomb model building is $v_{xmax}=10.7\ cm/s$, and in the HS Small model building it reaches $v_{xmax} = 11.8\ cm/s$.

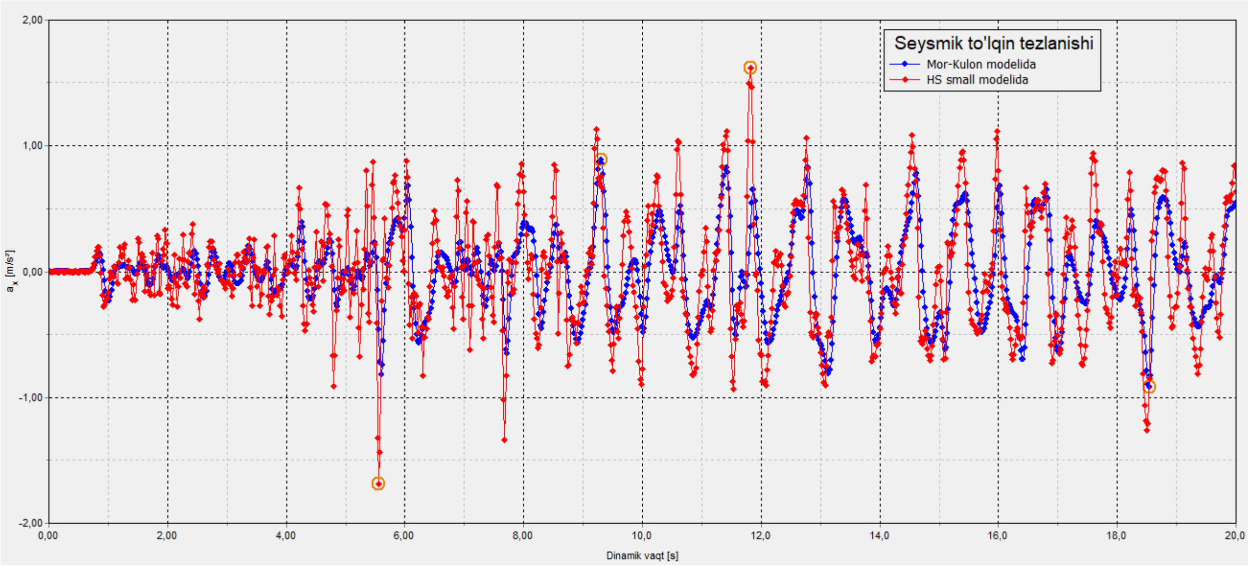


Fig. 5. A graph of the acceleration of a seismic wave along the x-axis

The maximum acceleration of the seismic wave along the x-axis reaches $a_{xmax}=91.7\ cm/s^2$ in the Mohr-Coulomb model building, and its maximum value is $a_{xmax}=168.9\ cm/s^2$ in the HS Small model building.

The table below shows and compares the maximum displacement, velocity and acceleration of the seismic wave at the level of the 1st floor of the building designed in both models.

Table 4

№	In the Mohr-Coulomb model	In the HS Small model	The difference between them in %
maximum displacement in the x-axis direction [*cm*]	1,39	1,5	8%
maximum velocity in the x-axis direction [*cm/s*]	10,7	11,8	10%
maximum acceleration in the x-axis direction [cm/s^2]	91,7	168,9	84%

CONCLUSION. Based on the results of the above graphs, the seismic wave acceleration, velocity and displacements obtained with respect to the point at the1st floor level of the building located in two different models, i.e. Mohr-Coulomb (blue color) and HS Small (red color) the difference is having larger values in the HS Small model building. In addition, we can see that the results of the HS Small model are more accurate than the results of the Mohr-Coulomb model. We can conclude from this that the use of the HS Small model in the study of seismic waves propagating in the ground leads to more accurate and reliable results. From this issue, it can be said that the selection of the appropriate ground model type in the study of the effects of seismic waves on buildings ensures the reliability of the results.

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